4

Radionavigation System Research and Development Summary

4.1 Overview

This section describes Federal Government research and development (R&D) activities relating to Federally provided radionavigation systems and their worldwide use by the U.S. Armed Forces and the civilian community. It is organized in two segments: (1) civil R&D efforts to be conducted by DOT and other Government organizations for civil purposes, and (2) DOD R&D.

DOT R&D activities emphasize applications for and enhancement of GPS for civil uses. GPS has broad multimodal civil and military applications; consequently, there is need for close cooperation between Federal agencies in its evaluation. Such a cooperative effort will minimize duplication of effort and promote maximum productivity from the limited resources available for civil research. DOT's participation in the evaluation and development of GPS ensures that benefits can be derived from DOD's advances in systems technology. DOT R&D activities may involve evaluations and simulations of low-cost receiver designs, evaluation of future technologies, and determination of future requirements for the certification of equipment.

DOD R&D activities mainly address evaluations by Armed Forces acquisition agencies that are identified by military mission requirements and national security considerations. For this reason, DOD R&D is defined to include all activities before the final acquisition of a navigation system in accordance with detailed system specifications.

Although there are some similarities between the DOD and DOT analyses, DOD military missions place more emphasis on security and anti-jam capabilities. Such factors as anti-jam capabilities, updating of inertial navigation systems, input sensors for weapon delivery, portability, and reliable operation under extreme environmental or combat conditions become very important in establishing the costs of the navigation equipment.

The relationship between DOT and DOD R&D programs is based on a continuing interchange of operational and technical information on radionavigation systems. DOD R&D will be coordinated with DOT R&D under the following guidelines:

- DOT will evaluate the costs of all radionavigation systems that meet identified civil user requirements.
- DOT will provide DOD with the most current information on civil user requirements that may have a significant impact on DOD-operated radionavigation systems.
- DOD will provide information to DOT on GPS receiver designs that may be applicable to civil receiver development.
- DOD/DOT will not constrain the use of SPS-based differential GPS service as long as applicable U.S. statutes and international agreements are adhered to.
- DOT will cooperate in the development of differential correction reference stations for the best possible differential/integrity network.
- DOT will continue to evaluate satellite radionavigation technologies for potential use in an international Global Navigation Satellite System (GNSS).

The specific civil R&D activities are discussed in the following sections. These activities have been coordinated to achieve efficient use of the limited funds available for R&D and to avoid duplication of effort. R&D tasks for the individual DOT agencies (FAA, USCG, MARAD, etc.) and related tasks by other government agencies are addressed and schedules have been specified if possible so that the results of the efforts will be of maximum usefulness to all participants in the program.

4.2 DOT R&D

DOT R&D activities have been conducted primarily by the USCG, the FAA, the FHWA, and ITS/JPO. Initially, efforts were directed primarily toward determining the capability of GPS to meet civil user needs in the air, marine, and land transportation communities. Subsequently, as it became apparent that the GPS capability to be provided to the civil community would not meet all user requirements, R&D efforts focused on ways of enhancing GPS to meet these civil needs. Many new efforts are focusing on the development of new and innovative applications of GPS.

4.2.1 Civil Aviation

The FAA, under the direction of the Secretary of Transportation, has the responsibility to operate safe, efficient air navigation services. To accomplish this, the United States must maintain a leadership role in the definition and development of future technologies while maintaining the appropriate standards and practices governing the use of GPS technology by the airlines, general aviation users, avionics manufacturers, and the traveling public.

The FAA's basic R&D activities for the introduction of GPS into the NAS are currently focused on the GPS WAAS to satisfy accuracy, coverage, reliability, and integrity for all phases of flight down through Category I precision approach. Additional R&D activities, such as LAAS, which exploit the full capabilities of GPS for civil aviation are continuing.

The FAA, through its GPS R&D program, is developing the requirements for use of GPS in the national airspace. This includes refining the appropriate standards for GPS airborne receivers and developing the air traffic control methodology for handling GPS area navigation aircraft operation in an environment with non-GPS equipped aircraft. The FAA has certified GPS as a supplemental means of navigation. The use of GPS as a primary means of navigation depends on the successful development, deployment, and operation of the WAAS, as well as the development of appropriate standards, operating procedures, and avionics. The objective of the FAA is to support the integration of GPS and DGPS into the NAS in an evolutionary manner. The evolving WAAS will be a key component of the NAS precision approach and landing architecture. The WAAS is projected to meet all requirements for Category I precision approach. The FAA has demonstrated the technical capability of LAAS to support Category II and III operations and is pursuing LAAS to meet the Category II/III precision approach requirements. Other augmentations and auxiliary/hybrid sensors may also be employed, and are currently being examined. There is close cooperation between FAA, DOD, and industry in these efforts. A Memorandum of Agreement between FAA and DOD to implement GPS for civil aviation was signed on May 15, 1992.

The FAA is actively supporting the activities of the ICAO and RTCA in the definition of the GNSS and associated implementation planning guidelines. The GNSS is intended to be a worldwide position, velocity and time determination system. ICAO has accepted the GPS and GLONASS as the constituent components of the GNSS and is actively developing SARPs. The GNSS will also require end-user receiver equipment, a system integrity monitoring function, and ground-based services augmented as necessary to support specific phases of flight. GPS will be the primary satellite constellation used for navigation during early GNSS implementation. The FAA's activities in support of ICAO and RTCA will ensure that satellite navigation capabilities are implemented in a timely and evolutionary manner on a global basis.

The FAA is actively pursuing technology related to GPS augmentation in order to achieve a new primary means of navigation capability. While several methods are being analyzed and developed, WAAS is fully endorsed and is being developed by the FAA. This satellite-based augmentation concept has been operationally demonstrated for use in all phases of flight with a system prototype. The system is expected to be operational beginning in 2000.

The FAA is actively participating in the implementation of a seamless global navigation system. In order to provide safe, efficient GNSS to the aviation users at a reduced cost with improved performance, the FAA is actively participating on GNSS panels working toward the final objective of implementation of "Free Flight" initiatives in the United States. The WAAS and LAAS will provide satellite navigation to all aviation users for all phases of flight down to a Category III precision approach. Research efforts for these two systems are broken out as follows:

WAAS R&D Activities:

- Quantify and mitigate both scintillation effects and rapid changes in ionospheric range delay.
- Address the likelihood and potential severity of interference on GPS and SBAS implementations.
- Ensure clock performance for SBAS internal and external interfaces.
- Investigate and define international connectivity requirements.

LAAS R&D Activities:

- Continue research into ground reference receiver multipath and corresponding techniques for mitigation.
- Explore and investigate various availability enhancements as a result of additional ranging sources provided by pseudolites, GLONASS, WAAS, and other satellites being considered for the WAAS payload.
- Investigate LAAS VHF Data Broadcast (VDB) optimization techniques and identify the most optimal signal generation techniques and broadcast format(s).
- Evaluate effects of RF interference on GPS ground reference receivers, and evaluate methods of mitigation.
- Evaluate methods of LAAS ground system integrity monitoring.

The FAA has established a number of grants and interagency agreements. Contracts are also in place with industry, academia, and other government agencies to leverage their expertise and capabilities in satellite navigation research. In addition, a number of cooperative and bilateral agreements are in place to facilitate and promote the international communication and information transfer for a seamless GNSS.

Possibilities exist to develop receiver avionics that combine two radionavigation signals, such as GPS/GLONASS, and thereby significantly improve user navigation performance. FAA, in cooperation with industry, is developing standards under which a specific system or combination of systems may be certified in aircraft conducting IFR, en route, and terminal area operations, including nonprecision approach.

Time-based navigation and ATC practices in the en route and terminal environment would involve issuing time-based clearances to certain aircraft which can navigate with sufficient precision to fly space-time profiles and arrive at points in space at specified times. Aircraft equipped with advanced flight navigation and management systems may be able to receive clearances directly from ground automation equipment, and follow such clearances automatically along trajectories of their choice, either to maximize fuel efficiency or to minimize time. This will also enhance the utilization efficiency of the NAS, allowing increased capacity without a proportional increase in infrastructure expenditures.

Automatic Dependent Surveillance (ADS) is defined as a function in which aircraft transmit position and altitude data derived from onboard systems via a datalink for use by air traffic control, other aircraft, and certain airport surface vehicles. Automatic dependent surveillance R&D will develop functions to permit tactical and strategic control of aircraft. Automated position report processing and analysis will result in nearly real-time monitoring of aircraft movement. Automatic flight plan deviation alerts and conflict probes will support reductions in separation minima and increased accommodation of user-preferred routes and trajectories. Graphic display of aircraft movement and automated processing of data messages, flight plans, and weather data will significantly improve the ability of the controller to interpret and respond to all situations without an increase in workload.

GPS-based navigation offers new opportunities for vertical-flight aircraft to operate more efficiently in the NAS. As prime examples, significant benefits have been derived through virtually uninterrupted emergency medical services to hospitals and trauma centers in all weather operations, undelayed passenger-carrying operations and optimized low-altitude air routes.

Emergency medical services have long recognized the importance of delivering prompt medical attention and expeditiously transporting patients to and between medical facilities. GPS-based navigation enhances this potential by enabling instrument approaches to every hospital with sufficient obstacle-free airspace. The FAA is investigating how best to maximize this new capability through reduced TERPS obstacle clearance areas, steeper glide slopes, and curved approaches for vertical-flight aircraft. The first stage of this testing focuses on nonprecision approaches. Tests of vertical-flight aircraft performance during nonprecision approaches are being conducted at four heliport sites. Data collection will focus on system-use accuracy and pilot workload over various combinations of glide slopes and curved approaches. Follow on testing will examine precision approach and en route navigation requirements. The results gained during these tests can also be applied to a wide variety of other vertical-flight aircraft missions.

Passenger-carrying operations using vertical-flight aircraft is one method of reducing congestion and delays at high activity airports and on highways. In terminal areas, however, this will work most efficiently if vertical-flight aircraft can operate independently of the regular fixed-wing traffic flow. The high accuracy of GPS-based navigation together with the unique flight capabilities of vertical-flight aircraft can enable undelayed approaches. The FAA is examining methods to optimize these traffic patterns and approaches into high activity airports to eliminate delays regardless of the weather.

The vertical-flight community has identified the need to have low altitude IFR routes that are nearly direct and separate from high traffic fixed-wing routes. Flying IFR at low altitudes is also important in many areas of the United States, most notably the northeast United States, to avoid the frequent icing conditions. Due to the limitations of VOR, only one such IFR route had been feasible. GPS-based navigation can enable these types of routes to be developed wherever a need exists. The FAA has begun analyzing these requirements and the best methods to integrate this route structure into the NAS.

4.2.2 Civil Marine

The USCG conducted mission needs analysis of DGPS with the following conclusions. DGPS can meet performance requirements to provide all weather navigation capability with a safety level equivalent to visual aids to navigation in most ports and waterways. However, mariners are still required to use all available means of navigation.

The Coast Guard is working to create a vision of marine navigation services for the 21st century. A central issue for the Coast Guard is to devise an evolving system of aids to navigation that safely and effectively accommodates new navigation technologies. The Aid Mix Project will provide the information and tools for this task. One goal of this project is to develop a set of analysis tools to allow performance evaluations of navigation systems in specific ports and waterways. These tools will help assess the relative level of safety expected from radio aids, navigation equipment, and short range aids to navigation intended to be used for harbor entrance and approach.

In addition, the USCG is exploring accuracy enhancement and the integration of DGPS with other navigation sensors. Particular emphasis is being placed upon the integration of DGPS with Inertial Navigation Systems (INS). Ongoing efforts are being conducted to determine the ability to INS to enhance DGPS/GPS navigation service, and to provide heading information for Electronic Chart Display Information System (ECDIS) use. Work with RTCM Special Committee 104 (SC104) in developing new high accuracy messages, including ones optimized for use with SA off, is being conducted. This work includes the development of corrections for ranging signals broadcast from geo-stationary satellites. Also, several promising improvements to the DGPS data link hold the potential to further mitigate the effects of impulse noise and interference and are being studied.

4.2.3 Civil Land

Land radionavigation users, unlike air and marine users, do not come under the legislative jurisdiction of any single agency. Several DOT organizations are conducting studies and analyses to determine requirements and applications of GPS.

In 1994, DOT conducted a study to evaluate the capabilities of augmented GPS technologies for meeting the requirements of aviation, land and marine users. As part of this task, the current requirements of these users were examined, and the augmented GPS options were evaluated to determine which, if any, could satisfy user requirements. The study concluded that no single augmentation system could meet all user requirements. It recommended an integrated approach that included the FAA's WAAS and LAAS for aviation users, an expanded USCG local area DGPS system for land and marine users, and

that all reference stations associated with these systems be compliant with the CORS standards developed by the NGS for post processing applications. Additionally, while a high level technical analysis was completed of the feasibility of expanding the USCG system inland, an in-depth analysis was needed to determine the technical feasibility of expanding the USCG system nationwide to meet the needs and requirements of Federal Government land-based users. The technical feasibility study, initiated in 1995 and concluded in April 1996, found that there were no major technical barriers to expanding the system nationwide. Implementation of the NDGPS began in 1997 with the installation of the proof of concept site in Appleton, WA. NDGPS implementation is expected to take five years with a target completion date of December 31, 2003.

In its first report, the NDGPS PIT revalidated the 1994 augmentation study and developed cost summaries for the full implementation. Implementation of the NDGPS service began in 1998 with the installation sites in Whitney, NE, Savannah, GA, and Chico, CA. Full implementation is expected to take 3-4 years with a target date of December 31, 2003.

Several agencies are already evaluating GPS and the new NDGPS for specific applications. For example, RSPA, as the DOT focal point for hazardous materials transportation and pipeline safety, will also study GPS tracking technologies.

Several departments and agencies of the Federal Government are sponsoring R&D activities that use existing radionavigation systems for various land uses. Federal and state governments and private industry are conducting research, as part of the ITS program, to assess the feasibility of using in-vehicle navigation and automatic vehicle location to satisfy the needs of ITS user services. A complete listing of R&D studies and operational tests wholly or partially funded by FHWA, FTA and NHTSA can be found in DOT's *Intelligent Transportation Systems Projects, January 1998* (Ref. 12). These tests are focused on the development of ITS user services to achieve improvements in safety, mobility, and productivity, and reduce harmful environmental impacts, particularly those caused by traffic congestion. The following paragraphs describe some of these tests.

The Onboard Automated Mileage Test in Iowa, Minnesota, and Wisconsin is a three state project that tested and evaluated the effectiveness of using GPS and first-generation onboard computers to record the miles driven within a state for fuel tax allocation purposes in a manner acceptable to state auditors. The system will automatically record mileage by specific roadway as well as state border crossings using GPS and vehicle location technology with a map-matching algorithm.

The Baltimore Mass Transit Administration (MTA) is implementing an Automatic Vehicle Location (AVL) system that will provide bus status information to the public while simultaneously improving bus schedule adherence and labor productivity. A prototype system involving 50 buses is being tested with Loran-C receivers and 800-MHz radios. The buses' location is determined by the receiver and the information is transmitted to a central dispatch center. Off-schedule buses are identified so corrective action can be taken. The system has been expanded to include all 900 Baltimore transit buses and GPS is replacing Loran-C for vehicle location.

Dallas Area Rapid Transit (DART) has installed an Integrated Radio System that includes AVL. When completely installed, 832 transit buses, 200 mobility impaired vans and 142

supervisory and support vehicles will be equipped. GPS will generate vehicle location information for fleet management and data collection purposes.

The Colorado Mayday System operational test calls for the installation of in-vehicle devices which are capable of capturing a snapshot of available GPS location data, and other vehicle related emergency information, and a communications system primarily based on cellular telephones and specialized mobile radio units. A control center will be established to receive and process emergency assistance requests from the in-vehicle units and determine vehicle location from the GPS data that were included in the emergency assistance request. The control center will determine the nature of the request and forward it to the appropriate response agency for action. The motorist will then be notified by the control center on the actions taken and the expected response time. The in-vehicle unit will be capable of automatically activating the emergency assistance request under some conditions where the driver may be incapacitated. In addition, there will be a button box that will allow the driver to initiate a specialized call for assistance ranging from vehicle service or repair to medical emergencies. The Denver, Colorado Rapid Transit District (RTD) Passenger Information Display System will use data gathered from the AVL system, currently being installed on all RTD buses, to provide information to video monitors at selected locations regarding estimated bus departures for waiting bus passengers.

The DOT is currently working to develop the Intelligent Transportation Infrastructure through the Model Deployment Program, gradually moving away from operational tests as new technologies are becoming commercially viable.

Several railroads and state governments and FRA are participating in and supporting several positive train control projects that use GPS and NDGPS for position and speed determination. Shown in Table 4-1, these projects are aimed at the development of safer, lower cost control systems for both freight and passenger train operations.

Table 4-1. Current Positive Train Control Projects Using GPS

Project	Sponsors	Location
Incremental Train Control System	Michigan DOT Amtrak FRA Harmon Electronics	Kalamazoo – New Buffalo, MI
Positive Train Control	Illinois DOT Association of American Railroads FRA	Springfield – Mazonia, IL
Precision Train Control	Alaska Railroad FRA GE-Harris	Seward – Anchorage – Fairbanks, AK
Communications-Based Train Management	CSX Wabco	Spartanburg, SC – Augusta, GA
Train Guard	Burlington Northern Santa Fe Railway Wabco	Los Angeles – Barstow, CA

4.3 NASA R&D

NASA is conducting R&D in a number of GPS application areas in the space, aeronautics, and terrestrial environments. These efforts include:

Space Applications: The emphasis in the space applications R&D of GPS is primarily on development of off-the-shelf GPS receivers that can be installed in satellites. These receivers will be capable of providing onboard navigation products, providing GPS time signals for distribution to spacecraft systems and instruments, providing necessary data for post-pass processing in support of science data collection, and determining spacecraft attitude. Some receivers will send GPS observables to the ground for processing of position information; however, the more advanced receivers will provide onboard autonomous position and navigation.

In addition to the direct use of GPS satellite information, NASA will be conducting research into the use of global GPS WAAS. Initial work in this area indicates that significant improvements will be achieved in real-time determination of satellite position through improved GPS satellite signal visibility as well as improved integrity protection for satellite users.

During the next few years, NASA, in conjunction with DOD and the international community, will be exploring the use of GPS at satellite altitudes extending to geosynchronous orbit.

NASA is also continuing to refine the post-pass processing techniques used to support precise analysis of scientific data requiring precise knowledge of spacecraft position at data collection time.

In addition, there is promising research being conducted in the use of spaceborne GPS receivers as scientific instruments for atmospheric research. This research involves the use of dual frequency GPS receivers to measure the occultation of the GPS satellite radio signals through the atmosphere. This research could lead to an important new instrument for use in weather forecasting.

Aeronautics Applications: NASA will continue to use GPS receivers aboard NASA aircraft for both aeronautics research and in support of airborne scientific observations. There are numerous projects throughout NASA where GPS technology is being developed for these purposes. Airborne GPS receivers have been used to support NASA scientific research in areas such as Airborne Synthetic Aperture Radar (AIRSAR) and in Greenland ice sheet thickness measurements, and it is anticipated that these uses of GPS will continue and expand.

Terrestrial Applications: NASA is supporting the continued development of the International GPS Service for Geodynamics (IGS). Areas of research include continued enhancement of the software used to determine GPS ephemerides and techniques for improving measurement accuracy to the 1 mm level.

4.4 NOAA R&D

NOAA performs GPS research and development aimed at (1) improved GPS orbit determination, (2) improved determination of the vertical coordinate using GPS, and (3) development of models of error sources that can improve the accuracy attainable using data from the CORS network of GPS reference stations. Some of the specific studies being undertaken are: improved modeling of tidal deformations of the Earth; development of models of antenna phase center variation as a function of elevation angle of a satellite; development of models of station specific multipath errors; development of improved models of geoid height required to convert GPS derived ellipsoid heights to orthometric heights; and development of improved computational models for determination of the vertical coordinate.

NOAA is also developing operational methods of using GPS derived total precipitable water vapor determinations in weather prediction and climate models and is investigating methods of improving the accuracy of the precipitable water vapor determinations. Finally, studies are underway to improve the methods used to position and orient aircraft performing photogrammetry in support of nautical and aeronautical charting.

4.5 DOD R&D

GPS Security Program

The PDD announced that it was the U.S. intention to discontinue the use of GPS Selective Availability (SA) within a decade (2006) in a manner that allows adequate time and resources for military forces to prepare for operations without SA.

The DOD has initiated a Navigation Warfare (NAVWAR) program that provides the warfighter with the tools to effectively employ GPS as a force multiplier on the 21st Century battlefield. The effort provides for the incorporation of advanced technologies to meet emerging mission requirements while countering theater threats. There are three elements to the NAVWAR effort: protection, prevention, and sustainment of civil use. Protection is the ability of U.S., Allied, and Coalition forces to operate in a challenged electronic warfare environment. Prevention is the ability to prevent an adversary's use of GPS technologies against us. There must be an integration of protection and prevention technologies to ensure optimal use of GPS on the battlefield. In addition, civil use of GPS outside a theater of operations or area of responsibility must not be adversely impacted by the military's exploitation of the electromagnetic spectrum. NAVWAR is designed to preserve civil user service by providing a regional or local protection and prevention capability, thus satisfying the U.S. commitment to provide SPS service on a worldwide basis.

This R&D effort will require periodic testing which may impact the civil use of GPS. DOD and DOT are developing mechanisms to coordinate times and places for testing, and to notify users in advance.

Joint Precision Approach and Landing System

The DOD has established the JPALS program to provide its next generation precision approach and landing system capability. JPALS provides for U.S. forces to perform assigned conventional and special operations missions from fixed base, tactical, shipboard, and special mission environments under a wide range of meteorological conditions. No existing system satisfies the mission need for worldwide deployment and interoperability among the Services and Civil Reserve Air Fleet (CRAF). Interoperability with the national and international civil precision approach systems (such as the FAA's WAAS and LAAS) is also driving the need for JPALS.

The DOD has designated the Air Force as the lead service for JPALS. The October 1997 Analysis of Alternatives (AoA) recommended the most promising alternative in the land based environments (and in conjunction with the Automatic Carrier Landing System in the shipboard environment). In addition, the AoA identified several critical risk areas requiring further research and development. On 14 Sep 98, the Under Secretary of Defense for Acquisition and Technology (USD (A&T)) formally approved the JPALS program to enter a three-year Architecture and Requirements Development (ARD) phase. In this phase, LDGPS and ACLS systems will be prototyped and tested, and analyses and programmatic assessments conducted, in order to meet the following four objectives:

- Provide sufficient evidence that key technical risks have been reduced, including the areas of 1) guidance quality, 2) signal-in-space availability, 3) transportability, 4) set-up time and personnel, 5) probability of detection, classification, and exploitation, 6) vulnerability to signal disruption/spoofing, 7) shipboard compatibility, and 8) standardization, interoperability, and commonality. A key risk area identified in the JPALS AoA is the compatibility of JPALS with GPS anti-jamming enhancements such as those developed under the NAVWAR program.

- Define the JPALS technical architecture. The architecture must be supported by a set of standards and technical documentation (e.g., specifications) and risk assessments that provide sufficient evidence that risks associated with meeting the critical performance parameters have been reduced or mitigated.

- Synchronize JPALS with other programs such as the FAA's WAAS and LAAS, the GPS JPO NAVWAR program, the Army Navy, and Marine Corps Communications, Navigation and Surveillance/Air Traffic Management (CNS/ATM) efforts and the Air Force Global Air Traffic Management (GATM) effort.

- Provide data to support the milestone decision, including an acquisition strategy for the development, integration, installation and production of JPALS systems.

One implementation of JPALS that provides for maximum interoperability is the multi-mode receiver (MMR). Initially developed to provide both MLS and ILS capabilities, the USAF successfully demonstrated the insertion of a GPS card in the production MMR. In 1995, the prototype MMR successfully conducted numerous approaches against a prototype SCAT-I landing system with CAT I or better accuracy. The multi-mode

solution is planned for expansion to include WAAS, LAAS, and the P/Y-code LDGPS capability as developed in the JPALS R&D program.

Improvements in Precise Time and Time Interval (PTTI)

Over the past several decades, developments in technology for all military electronic systems have led to greater requirements for PTTI. Interoperability of systems throughout all the Services, as well as with NATO, requires accurate common time. Within the next decade, it is anticipated that requirements for PTTI at the 1 part in 10 to the 15th per day (1ps) will exist. In order to prepare for this stringent requirement, the U.S. Naval Observatory, as the provider of the DOD precise reference for time, has begun research and development efforts in advanced clock design and in clock analysis algorithms. In order to better disseminate the time reference, the USNO is developing a Distributed Master Clock System as well as investigating new techniques for time transfer. The Two-Way Time and Frequency Satellite Time Transfer System is currently under tests for very high precision users.

The importance of PTTI technology throughout DOD was recognized in the Special Technology Area Review on Frequency Control Devices (STAR), February 1, 1996. It reported that frequency control device technology is of vital importance to the DOD since the accuracy and stability of frequency sources and clocks are key determinants of the performance of radar, C3I, navigation, surveillance, EW, missile guidance, and IFF systems.

The report continues with some R&D opportunities with potential for meeting future DOD needs. These opportunities include development in high perfection quartz; new piezoelectric materials; resonator theory, modeling and computer-aided design of resonators and oscillators; processing and packaging of high stability resonators; microresonators and thin film resonators; low power, high, accuracy quartz clocks; low noise resonators and oscillators; smart clocks; miniature and high-performance optically pumped atomic clocks; and resonator based chemical, biological and uncooled infrared sensors.